Capacity reduction in railway prestressed concrete sleepers due to dynamic abrasions

Ngamkhanong, Chayut; Li, Dan; Remennikov, Alex; Kaewunruen, Sakdirat

CAPACITY REDUCTION IN RAILWAY PRESTRESSED CONCRETE SLEEPERS DUE TO DYNAMIC ABRASIONS

Chayut Ngamkhanong[1,2], Dan Li[1,2] and Alex M Remennikov[3] and Sakdirat Kaewunruen[1,2]

[1] *Department of Civil Engineering, The University of Birmingham, U.K.*

[2] *Birmingham Centre for Railway Research and Education, The University of Birmingham, U.K*

[3] *School of Civil, Mining and Environmental Engineering, University of Wollongong, Australia*

ABSTRACT

Railway prestressed concrete sleepers often experience significant aggressive loading conditions and environmental effects. Especially in sharp curves, lateral loading of trains in combination with incompressible hydraulic pressure aggravates the lateral oscillation and abrade the surface of sleepers right underneath the rail seats. Many investigators in the past have proposed various material models to improve abrasive resistance characteristics but those have been mostly applied to the new products using novel materials such as fibre-reinforced concrete. However, prestressed concrete sleepers have been used for over 50 years and they have worn over time. This paper highlights the capacity evaluation of worn sleepers, which will lead to predictive models that could be realistically applied to operation management of railway lines. This paper presents an investigation into the structural capacity reduction in worn railway prestressed concrete sleepers. RESPONSE2000 has been used to evaluate the residual capacity based on the compression field theory. The study results exhibit the level of wear and tear, which is critical to the integrity of sleepers and is required for immediate replacement. The improved understanding from this paper will help update the practical maintenance issues in railway industry.

Keywords: prestressed concrete, sleepers, abrasion, railseat abrasion, soffit abrasion.

1. INTRODUCTION

Railway sleepers (also called 'railroad tie' in North America) are a main part of railway track structures. Railway sleepers embedded in ballasted railway tracks are laid to support the rails. Notably, railway prestressed concrete sleepers have been used in railway industry for over 50 years (Kaewunruen and Remenikov 2006, 2007). The sleepers can be typically made of timber, concrete, steel or other engineered materials (Esveld 2001). Their key duty is to redistribute loads from the rails to the underlying ballast bed and to secure rail gauge and enable safe passages of rolling stocks.It is important to note that railway sleepers are a structural and safety-critical component in railway track systems (Fryba 1996, Gamage et.al. 2015, Kaewunruen and Remenikov 2009, 2013, Remenikov et.al. 2007, 2012).

Railway track structures often experience impact loading conditions due to wheel/rail interactions associated with abnormalities in either a wheel or a rail (Remennikov and Kaewunruen 2008). Generally, dynamic shock loading corresponds to the frequency range from 0 to 2000 Hz due to modern track vehicles. Wheel/rail irregularities induce high dynamic impact forces along the rails that may greatly exceed the static wheel load. In all cases, the impact forces are significantly dependent on the train speed. These impulses would occur repetitively during the roll. Loss of contact between wheel/rail, so-called "wheel fly", will occur if the irregularity is large enough, or the speed is fast enough. However, the impact force could be simplified as a shock pulse acting after the static wheel load is removed.

Previous work revealed that most of the numerical and analytical models employed the concept of beam on elastic foundation where a sleeper is laid on the elastic support, acting like a series of springs. In practice, the lateral force is less than 20% of vertical force and the anchorage of fastening has been designed to take care of lateral actions (Rahrovani 2016). In fact, field measurements suggest a diverse range of sleeper flexural behaviors, which are largely dependent on the support condition induced by ballast packing and tamping (Gustavson 2002, Kaewunruen and Remenikov 2007, 2008). However, it is still questionable at large whether modern ballast tamping process is effective and it could enable adequate symmetrical support for sleeper at railseat areas. Over time, ballast densification at railseats is induced by dynamic broadband behaviours and the sleeper mid-span comes into contact or is fully supported by ballast until the track geometry is restored by resurfacing activity (i.e. re-tamping) (Kaewunruen et.al. 2011). At railseat, the dynamic loading condition gives a high change that the bottom of sleeper (or called 'soffit') may experience aggressive abrasive force, wearing out the materials in the region.

The critical literature review reveals that the dynamic behavior of railway sleepers has not been fully investigated, especially when the sleepers are deteriorated by excessive wears (Kaewunruen, and Remennikov 2008, 2010, Ngamkhanong 2017). Most common wears are railseat and soffit abrasion at railseat. These deterioration mechanisms can be observed in the fields. Although it is clear that the railway sleepers can experience dynamic lateral wears, such the aspect has never been fully investigated. This paper is the world first to investigate and present an advanced railway concrete sleeper modelling capable of parametric analysis into the effect of surface abrasion together with strain rate on the dynamic behaviors of railway sleepers. The emphasis of this study has been placed on the impact capacity of the crossties with abrasion. The improved understanding from this paper will help update the practical maintenance issues in railway industry.

2. PREDICTION FOR ULTIMATE MOMENT CAPACITY

2.1. Modified compression field theory

In this study, the ultimate moment has been used to represent the capacity of prestressed concrete sleepers. The moment capacities are predicted by the modified compression field theory using

Response-2000 (Bentz 2000). This theory is capable of predicting the behaviour of reinforced concrete subjected to in-plane shear and normal stresses. The concrete stresses in principal directions along with prestressing steel are considered in only axial direction and uncracked portion will carry on to sustain a load in the analysis (Remennikov and Kaewunruen 2014).

2.2. Effect of strain and loading rates

Based on the assumption of perfect bond between prestressing wires and concrete, the strain rate plays an important role in material strengths. In this study, strain rate are varied to study the effect of strain rate to moment capacity under impact loading. The dynamic material properties of concrete and prestressing wires can be determined as follows (Wakui and Okuda 1999).

Concrete:

$$\frac{f'_{c,dyn}}{f'_{c,st}} = 1.49 + 0.268\log_{10}\dot{\varepsilon} + 0.035[\log_{10}\dot{\varepsilon}]^2 \quad (1)$$

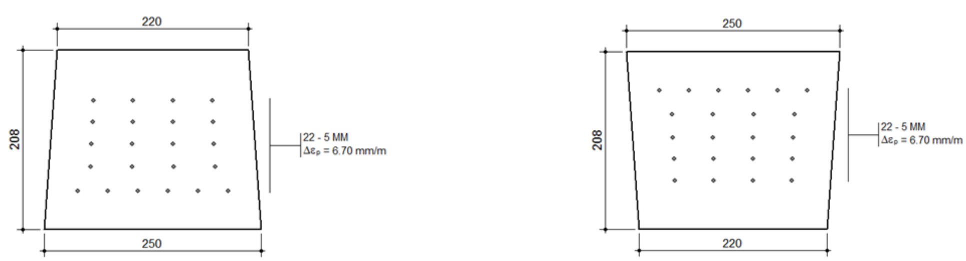
Prestreesing wires:

$$\frac{f_{y,dyn}}{f_{y,st}} = 10^{0.38\log_{10}\dot{\varepsilon}^{-0.258}} + 0.993 \quad (2)$$

Where $f_{y,dyn}$ is the dynamic upper yield point stress, $f'_{c,st}$ is the static upper yield point stress of prestressing wires (about 0.84 times proof stress), and $\dot{\varepsilon}$ is the strain rate in tendon.

3. MATERIAL PROPERTIES

In this study, 2 positions of prestressed concrete sleepers, which are normal position and inverse position, are comsidered in order to evaluate the positive and negative ultimate moment capacities, respectively, as shown in Fig 1.

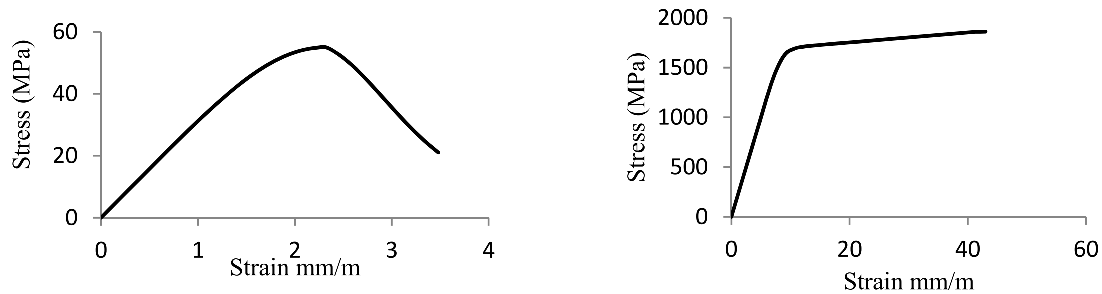


a) b)

Figure 1: Prestressed concrete sleepers in a) Normal position b) Inverse position

3.1. Static

The dimension and shape of prestressed concrete sleepers are shown in Figure 1.The high strength concrete was used with the design cylinder compressive strength of 55 MPa. The stress-strain curve of concrete derived by Vechio and Collin 1986 was used in this study, as shown in Figure 2. The 22- prestressing steels used were the high ultimate strength with rupture ultimate strength of 1860 MPa, as shown in Figure 2. The initial elastic modulus of prestressing steel was 20000 MPa.



(a) (b)

Figure 2: Stress-strain curve of a) concrete b) steel

3.2. Dynamic

The prediction of moment capacity has been carried out using the data obtained from the previous experiments (Kaewunruen and Remennikov 2009, Li et.al. 2017, Ngamkhanong et.al. 2017). It should be noted that the average total duration of impact forces is about 4 ms. In this study, the strain rate of concrete is varied from 2 ms to 8 ms. It is well known that the dynamic ultimate strain of prestressing steel is about $20x10^3$, and the total duration of impact force influencing the steel fibre is roughly from 6 ms to 12 ms. This is because the impact stress wave delays during the stress propagation and will be impeded through concrete (Wakui and Okuda 1999). The dynamic strength of materials can be obtained as the input for the sectional analysis using equation (1) and (2). The 4 pairs of strain rates variations are used in this study, as shown in Table 1.

Table 1: Strain rate variations under impact loading

Material	A	B	C	D
Concrete	2	4	6	8
Prestressing wires	6	8	10	12

4. RESULTS AND DISCUSSIONS

Using the material properties from section 3, the ultimate moment capacities of worn prestressed concrete sleepers, which are railseat abrasion and soffit abrasion, under static loading and impact loading can be illustrated in this section. As for railseat abrasion, the depth of prestressed concrete sleepers is reduced by 10 cm, 20 cm, and 30 cm, respectively, at the top surface. In term of soffit abrasion, the depth is reduced by 15 cm, 30 cm, and 45 cm until the position of lowest layer of prestressing steel. It is assumed that the steel still locate in the bottom position.

4.1. Static analysis

Table 2 demonstrates ultimate moment capacities of worn prestressed concrete sleepers under static loading. It exhibits that railseat abrasions play a dominant role on positive moment capacity of the worn sleepers, whilst negative moment capacity does not have similar effects. Moreover, it can be observed that soffit abrasion plays a little role on positive moment capacities of the worn sleepers. On the other hand, this mechanism can be a significant effect on negative moment capacity reduction.

Table 2: Ultimate moment capacities of prestressed concrete sleepers under static loading

Worn depth (cm)		Recorded moment capacity (kNm)	
Railseat	**Soffit**	**Positive**	**Negative**
Full cross section		59.30	47.50
10	0	52.50	47.40
20	0	45.80	47.30
30	0	39.40	47.00
0	15	59.00	37.40
0	30	58.50	28.10
0	45	58.00	19.80

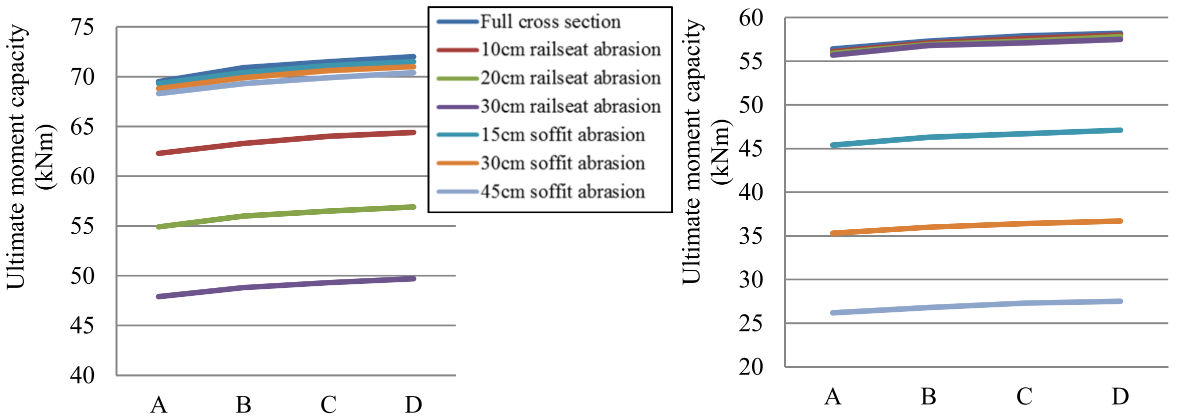
4.2. Dynamic analysis

Apart from effect from worn depth, 4 pairs of strain rate are taken into account based on perfect bond between prestressing wires and concrete. Table 3 shows the ultimate moment capacities of prestressed concrete sleepers under impact loading at different strain rate.

Table 3: Ultimate moment capacities of prestressed concrete sleepers under impact loading

Worn depth (cm)		Recorded moment capacity (kN-m)							
		A		B		C		D	
Railseat	**Soffit**	**Positive**	**Negative**	**Positive**	**Negative**	**Positive**	**Negative**	**Positive**	**Negative**
Full cross section		69.50	56.40	70.90	57.30	71.50	57.90	72.00	58.20
10	0	62.30	56.10	63.30	57.10	64.00	57.60	64.40	58.00
20	0	54.90	55.90	56.00	56.90	56.50	57.30	56.90	57.80
30	0	47.90	55.70	48.80	56.80	49.30	57.10	49.70	57.50
0	15	69.30	45.40	70.40	46.30	71.10	46.70	71.50	47.10
0	30	68.80	35.30	69.90	36.00	70.60	36.40	71.00	36.70
0	45	68.30	26.20	69.30	26.80	69.90	27.30	70.40	27.50

In case of railseat abrasion, it can be observed that moment capacities of worn sleepers are about 70% and 99% for normal and inverse position, respectively, of moment capacities of full cross-sectional area by 30 cm increasing in worn depth. As for soffit abrasion, about 98% and 60% of moment capacities in full cross-sectional area are observed when worn depth reaches 45 cm.



a) b)

Figure 3: Ultimate moment capacity at different strain rates in a) positive b) negative

As for strain rate, it can be seen from Figure 3 that strain rate also play a role in moment capacity in concrete sleepers. The moment capacity show an upward trend when the strain rates are increased with the same rate at any case of mechanisms.

5. CONCLUSION

This study is the world first to investigate the effect of surface abrasion on the impact capacity of railway prestressed concrete sleepers. It exhibits that the surface abrasion undermines strength and impact capacity of railway concrete sleepers. Based on a critical literature review, it can be seen that the degradation of railway concrete sleepers in dynamic analysis has not been considered in previous research work in open literature. In fact, the ballast angularity causes differential abrasions on the soffit or bottom surface of sleepers (especially at railseat zone). Furthermore, in sharp curves and rapid gradient change, longitudinal and lateral dynamics of rails increase the likelihood of railseat abrasions in concrete sleepers due to the unbalanced loading conditions. Therefore, it is essentially important for track and rail engineers to assure that the modification or retrofitting of concrete sleepers at construction sites is carried out in a proper manner. By the results obtained from these unprecedented studies, it is found that the soffit abrasion plays a critical role on negative moment capacity reduction. Moreover, the railseat abrasion can reduce the positive moment capacity of the sleepers. Also, strain rate play a role on the moment capacity under impact load especially when the strain rate is high. The insight into the impact behavior of the concrete sleepers with surface abrasion will enable safer built environments in railway corridor, especially for concrete sleepers whose structural inspection is very difficult in practice.

6. ACKNOWLEDGMENTS

The first author gratefully appreciates the School of Engineering and Birmingham Centre for Railway Research and Education of his PhD scholarship. The second author is grateful to Australian Academy of Science (AAS) and Japan Society for the Promotion of Sciences (JSPS) for his JSPS Invitation Fellowship for Research (Long-term), Grant No. JSPS-L15701, at Railway Technical Research Institute (RTRI) and the University of Tokyo, Japan. The authors are sincerely grateful to European Commission for the financial sponsorship of the H2020-MSCA-RISE Project No. 691135 "RISEN: Rail Infrastructure Systems Engineering Network," which enables a global research network that tackles the grand challenge in railway infrastructure resilience and advanced sensing.

7. CITATIONS AND REFERENCES

Bentz EC (2000), "Sectional analysis of reinforced concrete members" (University of Toronto, Department of Civil Engineering)

Esveld C (2001), Modern Railway Track The Netherlands MRT Press.

Fryba L (1996), "Dynamics of railway bridges," Thomas Telford Czech Republic.

Gamage E, Kaewunruen S, and Remennikov A M (2015), "Design of holes and web openings in railway prestressed concrete sleepers," Railway Engineering Conference (Edinburgh UK).

Gustavson R (2002), "Structural behaviour of concrete railway sleepers" (Chalmers University of Technology, Department of Applied Mechanics)

Kaewunruen S, and Remennikov A M (2006), "Sensitivity analysis of free vibration characteristics of an in-situ railway concrete sleeper to variations of rail pad parameters," Journal of Sound and Vibration, 298(1), 453-461.

Kaewunruen S, and Remennikov A M (2007), "Investigation of free vibrations of voided concrete sleepers in railway track system," Proceedings of the Institution of Mechanical Engineers Part F: Journal of Rail and Rapid Transit, 221(4), 495-507

Kaewunruen S, Remennikov A M (2007), "Effect of improper ballast packing /tamping on dynamic behaviours of on-track railway concrete sleeper," International Journal of Structural Stability and Dynamics, 7(1), 167-177.

Kaewunruen S, and Remennikov A M (2008), "Experimental simulation of the railway ballast by resilient materials and its verification by modal testing," Experimental Techniques, 32(4), 29-35.

Kaewunruen S, and Remennikov A M (2009), "Dynamic flexural influence on a railway concrete sleeper in track system due to a single wheel impact," Engineering Failure Analysis, 16(3), 705-712.

Kaewunruen S, and Remennikov A M (2009), "Structural safety of railway prestressed concrete sleepers," Aust. J. Struct. Eng, 9(2), 129–140.

Kaewunruen S and Remennikov A (2009), "Impact capacity of railway prestressed concrete sleepers Engineering Failure Analysis," 16(5), 1520-1532.

Kaewunruen S, and Remennikov A M (2010), "Dynamic properties of railway track and its components: recent findings and future research direction," Insight-Non-Destructive Testing and Condition Monitoring, 52(1), 20-22(3)

Kaewunruen S, Remennikov A M and Aikawa A (2011), "A numerical study to evaluate dynamic responses of voided concrete railway sleepers to impact loading," Acoustics 2011: Breaking New Ground, 1-8.

Kaewunruen S, Remennikov A M and Murray M H (2012), "Limit states design of railway concrete sleepers ," Proc. of ICE Transport, 164(TR1).

Kaewunruen S, and Remennikov A.M (2013), "On the residual energy toughness of prestressed concrete sleepers in railway track structures subjected to repeated impact loads," Electronic Journal of Structural Engineering, 13(1), 41-61.

Kaewunruen S (2014), "Monitoring structural deterioration of railway turnout systems via dynamic wheel/rail interaction," Case Studies in Nondestructive Testing and Evaluation, 1(1), 19-24.

Kaewunruen S, Minoura S, Watanabe T, and Remennikov A.M (2016), "Remaining service life of railway prestressed concrete sleepers," Proceedings of International RILEM Conference on Materials, Systems and Structures in Civil Engineering (22-24 August 2016, Technical University of Denmark, Lyngby, Denmark).

Kaewunruen S, and Chamniprasart K (2016), "Damage analysis of spot replacement sleepers interspersed in ballasted railway tracks," Proceedings of the 29th Nordic Conference on Computational Mechanics (Chalmers University of Technology, Gotenburg, Sweden).

Li D, Ngamkhanong C and Kaewunruen S (2017), "Influence of vertical holes on creep and shrinkage of railway prestressed concrete sleepers," International Conference on Building up Efficient and Sustainable Transport Infrastructure, Prague, Czech Republic, September 21-22

Ngamkhanong C, Li D, and Kaewunruen S (2017), "Impact capacity reduction in railway prestressed concrete sleepers with vertical holes," International Conference on Building up Efficient and Sustainable Transport Infrastructure, Prague, Czech Republic, September 21-22

Ngamkhanong C, Li D, and Kaewunruen S (2017), "Impact capacity reduction in railway prestressed concrete sleepers with surface abrasions," World multidisciplinary civil engineering-architecture-urban planning symposium, Prague, Czech Republic, June 12-16.

Rahrovani S (2016), "Structural Reliability and Identification with Stochastic Simulation: Application to Raiway Mechanics,"(Chalmers University of Technology, Department of Applied Mechanics).'

Remennikov A M, Murray M H, and Kaewunruen S (2007), "Conversion of AS1085.14 for railway prestressed concrete sleeper to limit states design format," AusRAIL Plus 2 (Dec 2-6, Sydney, Australia).

Remennikov A M and Kaewunruen S (2008), "A review on loading conditions for railway track structures due to wheel and rail vertical interactions," Structural Control and Health Monitoring, 15(2), 207-234.

Remennikov A M, and Kaewunruen S (2009), "Reliability based design of railway prestressed concrete sleepers," Reliability engineering advances (Ed Hayworth G. I.) (Nova Science Publishers, Hauppauge, New York, USA) ISBN 978-1-60692-329-0 Ch 3.

Remennikov A M, Murray M H, and Kaewunruen S (2012), "Reliability based conversion of a structural design code for prestressed concrete sleepers," Proceedings of the Institution of Mechanical Engineers: Part F Journal of Rail and Rapid Transit, 226(2), 155-173.

Remennikov A M, and Kaewunruen S (2014), "Experimental load rating of aged railway concrete sleepers," Engineering Structures, 76(1), 147-162.

Standards Australia (2009), "Design of concrete structures," Australian Standard AS3600.

Standards Australia (2005), "Reliability-based design of structures," Australian Standard AS5104.

Vecchio FJ and Collins MP (1986), "The modified compression field theory for reinforced concrete elements subjected to shear," J Am Concr Inst , 83(2), 219–31

Wakui H and Okuda H (1999), "A study on limit-state design for prestressed concrete sleepers," Concr Lib JSCE 33, 1–25.